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Design of Upper/Lower System with Automatic Height Control for CNC Gas Cutting

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Abstract. CNC gas cutting machines are essential equipment in the heavy industry sector, widely used for precision cutting and high productivity in processing thick steel plates (8-300mm). These machines operate based on a CNC gantry structure, enabling movement along the X-axis (longitudinal) and Y-axis (transverse) to perform cutting operations. The quality of the cutting process heavily depends on flame control, maintaining the gap between the torch and the workpiece, and cutting speed. However, maintaining a consistent gap is challenging during large steel plate operations, often requiring manual adjustment by the operator.

Although automatic height control and ignition systems have been developed, they face limitations such as torch interference, system instability, and frequent maintenance or replacement, resulting in continued reliance on manual operation in most workplaces. To address these challenges and achieve complete automation of the gas cutting process, the development of a high-performance system that integrates automatic height control and automatic ignition functionality is critical. Such a system can enhance cutting quality, improve operational efficiency, and ensure greater safety for operators.

This paper proposes the design and implementation of an automatic height control system for CNC gas cutting machines. A ring-shaped capacitive sensor is employed to ensure precise and consistent height control, while an STM32 microcontroller is

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utilized for processing sensor signals and managing the control system. To validate the reliability of the designed system, finite element analysis (FEA) was conducted, followed by experimental verification to demonstrate its performance.

Keywords; Automatic torch height control; Automatic Ignition; Gas cutting torch; Up&Down System; All-in-one

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1. Introduction

CNC gas cutting machines are indispensable tools in the heavy industry sector, designed to provide high precision and productivity in the processing of thick steel plates ranging from 8mm to 300mm in thickness. These machines utilize a CNC gantry structure for movement along both X-axis (longitudinal) and Y-axis (transverse) to perform cutting operations with high accuracy. However, the cutting quality is highly dependent on several factors, including flame control, the gap between the torch and the workpiece, and the cutting speed. Maintaining a consistent torch-to-workpiece gap, particularly for large steel plates, remains a significant challenge, often requiring manual intervention by skilled operators [1,2].

Efforts to automate these processes have led to the development of automatic height control and ignition systems. Despite these advancements, existing systems suffer from various limitations, such as interference between torches, instability in operation, and frequent maintenance requirements. These challenges result in low adoption rates and continued reliance on manual adjustments in most industrial settings.

To address these challenges, a high-performance CNC gas cutting system integrating automatic height control and automatic ignition functionalities is essential. Such a system offers several key benefits:

- **High-quality cutting**: Maintains a consistent gap and achieves precise flame control to improve cutting quality.
- **Operator safety**: Reduces risks associated with manual ignition and adjustments, creating a safer working environment.

- **Automation and unmanned operation**: Minimizes operator intervention, enhancing productivity and maximizing operational efficiency.

A gas cutting torch with integrated automatic height control and ignition functions is a critical technology for improving cutting quality, ensuring operator safety, and achieving automation and unmanned operation. The development of such a high-performance CNC gas cutting system has become a significant research and industrial priority [3,4].

This paper presents the design and implementation of an advanced automatic height control system for CNC gas cutting machines. The proposed system employs a ring-shaped capacitive sensor to achieve accurate and consistent height control, with an STM32 microcontroller managing the sensor signal processing and overall control logic. The reliability of the designed system was evaluated through finite element analysis (FEA) and experimentally validated to ensure optimal performance. By overcoming the limitations of existing systems, this innovative approach aims to improve cutting quality, operational efficiency, and workplace safety, thereby contributing to the advancement of automation in the gas cutting industry.

2. Design of a capacitive sensor for automatic height control System in CNC gas cutting

A CNC gas cutting machine consists of a CNC gantry system that moves in the X-axis direction (longitudinal direction) along a rail, while multiple gas torches move in the Y-axis direction (transverse direction). A steel plate is placed on the worktable, and the gas torches are used for cutting. In most CNC gas cutting operations, large steel plates are placed on the worktable for cutting. However, since the gap between the workpiece and the torch is not uniform, an automatic height control system is required to maintain a consistent distance between the steel plate and the torch.

Figure 1. shows the configuration of the design of a capacitive sensor for an automatic height control system in CNC gas cutting.

The automatic height control system consists of a distance sensor that measures the gap between the workpiece and the gas torch, an electronic circuit for signal processing, an SEU (Single Event Upset) protection mechanism to ensure system reliability, and a height adjustment motor that controls the torch position based on the sensor signals.

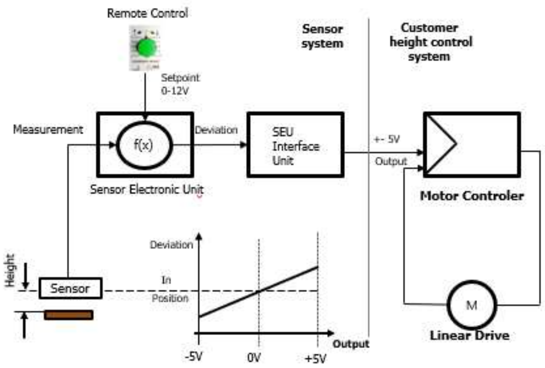

Figure 1. The total cost comparison of the HVDC and HVAC systems according to the lifetime

A. ***Operating principle of capacitive distance sensor***

A ring-type capacitive sensor detects changes in capacitance caused by variations in the distance of an object passing through its center, making it suitable for automatic height control in CNC gas cutting machines. The capacitance considering the fringe effect is expressed as follows:

$$C = \frac{\epsilon_0 \epsilon_r (0.5 + 0.222w/d)}{d} \quad (1)$$

where C is the capacitance, ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity, A is the effective area, w is width of the electrode and d is the distance between the sensor and the measured object. As the object moves closer, d decreases, increasing the capacitance, while moving away results in a decrease in capacitance.

The sensor consists of a sensing capacitor, an oscillator circuit, a charge amplifier, filtering, and a signal processing circuit, which converts capacitance changes into voltage signals for the CNC control system. The output voltage is given by:

$$V_{out} = k \cdot C \quad (2)$$

where V_{out} is the output voltage, k is the gain of the amplifier, and C is the measured capacitance. The ring-type structure provides advantages such as 360-degree detection, high-speed response, non-contact measurement, and high precision, ensuring stable performance in multi-torch systems and high-speed cutting environments. Additionally, it is resistant to heat and contamination, making it a reliable and efficient choice for automatic height control in CNC gas cutting applications.

B. Configuration of capacitive distance sensor

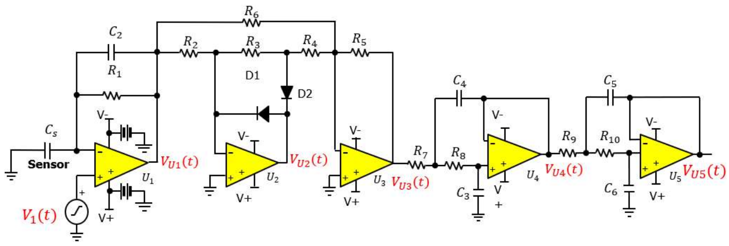

Figure 2. Circuit configurations for ring-type capacitive distance sensor

Figure 2 shows the circuit of the ring-type capacitive distance sensor of the automatic height adjustment system for CNC gas cutting. The entire circuit consists of an RC ociliator for signal generation, an integrator for signal conversion, an input amplifier, a comparator, an integrator for signal filtering, and an output amplifier to measure the parasitic capacitance between the actual cutting target and the sensor and transmit the corresponding signal. Each parameter of the ring-type capacitive distance sensor circuit is as shown in Table 1 below. Here, C_s is the parasitic capacitance between the cutting target and the sensor measured by the ring-type capacitive distance sensor, which is converted into the distance between the target and the sensor by the SEU interface unit.

Table 1. Parameters of the capacitor sensor circuit

Elements	Value
R_1	10 $M\Omega$
R_2, R_3, R_5, R_6	10 $k\Omega$
R_4	5 $k\Omega$
R_7	8.66 $k\Omega$
R_8	78.7 $k\Omega$
R_9	9.76 $k\Omega$
R_{10}	100 $k\Omega$
C_1, C_2	3 pF
C_3	680 pF
C_4	2.2 nF
C_5	220 pF
C_4	4.7 nF
C_s	Measured capacitance

3. Results and discussions

The capacitance (C_s) measured by the sensor according to the distance calculated by the formula in Chapter 2 is as follows Table 2.

Table 2. Capacitance according to distanc

Distance [mm]	Capacitance [pF]
0	8.7357
5	3.602
10	2.904
15	2.541
20	2.2967

To analyze the characteristics of the ring-type capacitive distance sensor, finite element analysis was performed on the entire circuit using the Matlab program according to the distance conditions. Figures 3, 4, and 5 show the signals (V_{U1}, V_{U3}, and V_{U5}) of each part of the distance sensor.

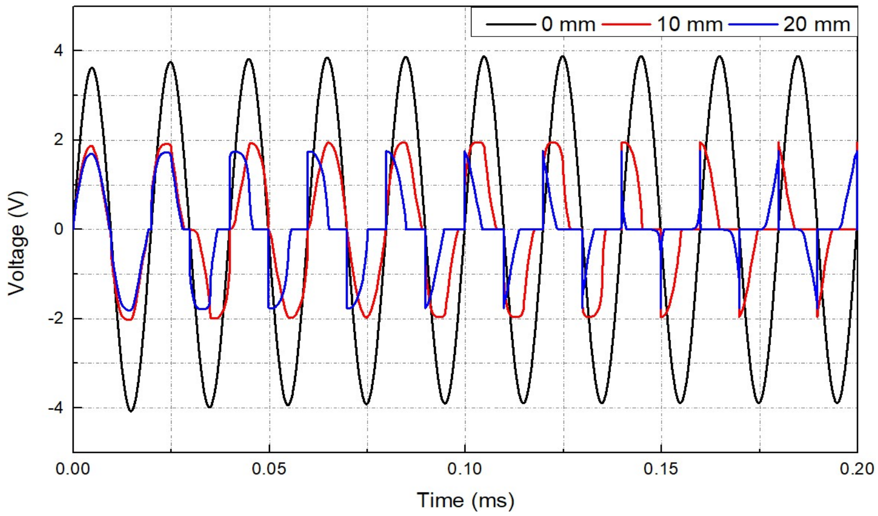

Figure 3. Distance sensor circuit simulation results (V_{U1})

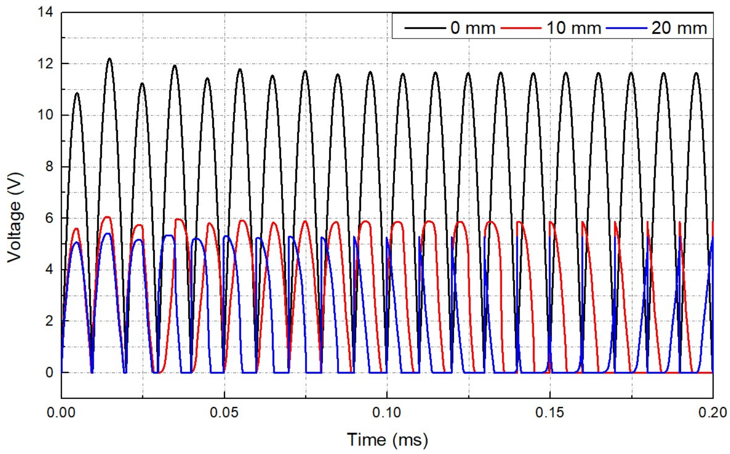

Figure 4. Distance sensor circuit simulation results (V_{U3})

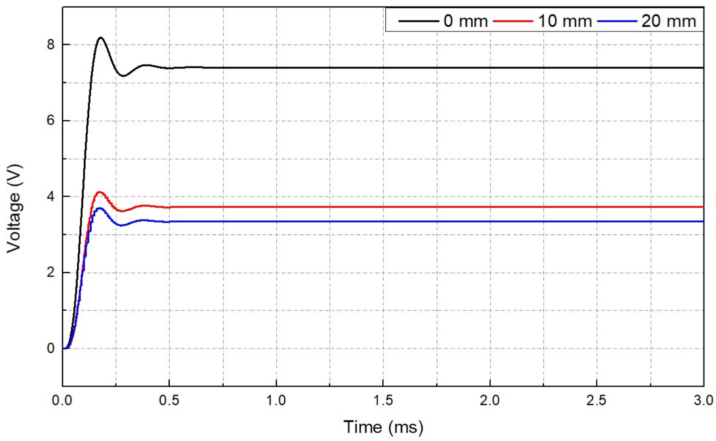

Figure 5. Distance sensor circuit simulation results (V_{U5})

The theoretical value of each part of the distance sensor is calculated using the following formula.

$$V_{U1} = R_1 \times 2\pi f(C_s + C_1) \times V_{1peak} = R_1 \times 2\pi f \times V_{1peak} \times \left(\frac{\varepsilon A}{d} + C_1\right) \quad (3)$$

$$V_{U3} = -V_{U1}\frac{R_5}{R_4} + V_{U1}\frac{R_2}{R_1}\frac{R_5}{R_3} = V_{U1}\left(-\frac{R_5}{R_4} + \frac{R_2}{R_1}\frac{R_5}{R_3}\right) \quad (4)$$

$$V_{U5} = \frac{R_8}{R_7}\frac{R_{10}}{R_9}V_{U3} \quad (5)$$

The signal values of V_{U1}, V_{U3}, and V_{U5} calculated using the formula are different from the values calculated by simulation.

Table 3. Capacitance according to distance

Distance [mm]	Calculated value ($V_{U1}/V_{U3}/\ V_{U5}$) [V]	Simulated value ($V_{U1}/V_{U3}/\ V_{U5}$) [V]
0	3.75/ 1.9/ 1.67	3.75/ 1.89/ 1.68
10	11.67/ 5.88/ 5.26	11.67/ 5.88/ 5.27
20	7.41/ 3.71/ 3.36	7.41/ 3.73/ 3.35

Finally, it can be seen that the error between the values of each part calculated by simulation and theoretical calculation is within an average of 5%.

4. Conclusion

This paper discusses the design of a ring-type capacitive distance sensor for an automatic height control system applied to CNC gas cutting machines. The proposed distance sensor consists of an RC oscillator for signal generation, an integrator for signal conversion, an input amplifier, a comparator, an additional integrator for signal filtering, and an output amplifier that measures the parasitic capacitance between the cutting target and the sensor and transmits the corresponding signal.

Using Finite Element Analysis (FEA), the voltage signals at each stage of the circuit were analyzed based on sensor measurement distance, and the simulation results showed an average error of approximately 5% compared to theoretical values. The development of the ring-type capacitive distance sensor, along with the integration of an SEU interface unit and a height control motor system, is expected to contribute to the realization of a fully automated height control system.

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